A Protocol for Topology-Dependent Transmission Scheduling in Wireless Networks

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Abstract— **A new channel access protocol for ad-hoc networks based on topology-dependent transmission scheduling, named collision-avoidance time allocation (CATA), is introduced. CATA allows nodes to contend for and reserve time slots by means of a distributed reservation and handshake mechanism. Contention is limited among nodes within two hops of one another, which provides a very efficient spatial reuse of the bandwidth available. CATA ensures that no collisions occur in successfully reserved time slots, even when hidden terminals exist. Reservations in CATA support unicasting, multicasting and broadcasting simultaneously, and adapt to dynamic service time. The throughput achieved by CATA is analyzed for the case of a fully-connected network topology. Numerical results show that CATA can achieve very high throughput.**

I. Introduction

AD-HOC networks (i.e., multi-hop packet radio networks) are an ideal technology to provide a seamless extension of the Internet to the wireless mobile environment. In ad-hoc networks, nodes (stations or packet radios) can be mobile and communicate with one another either directly or through intermediate nodes, without relying on any preexisting network infrastructure. The self-configuring, dynamic-connectivity, multihop-propagation and fully-distributed nature of ad-hoc networks makes them very attractive for many new applications but also introduce difficult problems at the link and network layer. In this paper, we focus on the medium access control (MAC) layer of ad-hoc networks, with which nodes coordinate their access to the shared radio channel.

Many MAC protocols have been developed for ad-hoc networks. The carrier-sense multiple access (CSMA) protocol was the first to be used in multihop packet-radio networks [1]. CSMA in multihop networks suffers from the *hidden terminal* interference, which degrades CSMA's performance to that of the pure ALOHA protocol [2]. Following the work by Tobagi and Kleinrock [3] to solve the hidden-terminal problems of CSMA, many collision-avoidance MAC protocols have been proposed, which include MACA [4], MACAW [5], IEEE802.11 [6] and FAMA [7]. These protocols use three-, four- or even five-way "collision-avoidance" handshakes based on small control packets meant to avoid data collisions when sources of data packets cannot hear one another.

Two key performance limitations of *all* collision-avoidance MAC protocols are that: (a) they do not support real-time applications; and (b) they lack explicit support of multicasting or broadcasting, which implies that either a node must transmit the same multicast packet multiple times, once to each multicast-group neighbor, or packets are sent with likelihood of reception as low as the ALOHA protocol.

Another approach to channel access used in multihop wireless networks consists of establishing transmission schedules, i.e., allocating stations to different times (time slots) in a way that no collisions occur. Because the minimum-length scheduling problem is NP-complete [8], [9] and normally needs complete topology information, most of the work on MAC protocols based on transmission scheduling has focused on distributed sub-optimal solutions targeted at conflict-free scheduling [9], [10], [11], [12], [13], [14]. Dynamic transmission-scheduling schemes exploit spatial reuse of the radio channel and thus have much higher channel utilization than fixed scheduling approaches, such as TDMA. However, all transmission-scheduling MAC protocols to date are designed either for broadcasting (node scheduling) or unicasting (link scheduling), but not both.

An interesting class of MAC protocols proposed recently is based on topology-independent dynamic scheduling [15], [16]. The basic idea is for a node to transmit in a number of time slots in each frame. The time slots when a node i transmits in a frame corresponds to a unique code such that, for any given neighbor k of i, node i has at least one transmission slot during which k and none of k's own neighbors are transmitting. Therefore, within any given frame time, any neighbor of i can receive at least one packet from i collision-free. The limitations of the topology-independent scheduling approaches described to date are that: (a) the sender is unable to know which neighbor(s) can correctly receive the packet it sends in a particular slot, which implies that the sender has to send its packet in the various slots it has available in a frame, and (b) the frame length (number of slots) must be larger than the number of nodes in a two-hop neighborhood, which is less scalable.

In this paper, we introduce the collision-avoidance time allocation (CATA) protocol for channel access control in ad-hoc networks. CATA is based on dynamic topology-dependent transmission scheduling and employs similar handshake procedures as those used in collision-avoidance MAC protocols [4]-[7] and prior approaches to topology-dependent time scheduling [11], [14] to eliminate the hidden-terminal problem and make reservations. CATA adopts the reservation signaling scheme for ad-hoc networks we first introduced in HRMA [17] to maintain reservations, which makes CATA adapt to dynamic traffic service time. After a successful reservation, a sender is able to transmit

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collision-free data packets on the reserved time slots in the following frames, until the reservation is terminated; accordingly, CATA supports real-time applications like other reservation or scheduling protocols. CATA differs from previous topology-dependent transmission scheduling protocols in that it supports broadcast, multicast and unicast transmissions simultaneously and is more adaptive to the dynamic traffic.

The remainder of the paper is organized as follows. Section II specifies CATA in detail. In section III, we prove that in CATA, data packets are sent collision-free in the presence of hidden terminals. Frame length in CATA is also discussed. Section IV provides an approximate throughput analysis of CATA for a fully-connected topology, which is tractable analytically and provides useful insight (lower bound) on the performance of CATA in general topologies, and some numerical results showing that CATA achieves very high throughput for the range of traffic load within which the network is stable. Section V presents our conclusions.

II. Collision-Avoidance Time Allocation

A. Protocol Description

We assume that the radios used are half-duplex and the physical links are bi-directional. The receiver of an active radio is always on while it is not transmitting. Time is slotted and slots are grouped into frames like previous protocols based on transmission scheduling. CATA's basic service consists of reserving collision-free time slots for unicasting, multicasting or broadcasting. Our description and analysis of CATA assumes a non-persistent retransmission policy for slot reservations; however, other policies are also possible.

For convenience, we refer to all the data that must be transmitted by a node to one or multiple neighbors over a given collision-free time slot as a *flow* or *message*. Data packets in the same message, therefore, can be addressed to different network-level destinations sharing the same relay. We assume that, at the sender side, the LLC (logical link control) protocol above CATA notifies CATA of the end of a reservation, and that the end of a reservation can be notified to the receiver(s) by the data packets sent in the flow or message.

Small control packets are used for nodes to contend for and reserve slots. The operation of CATA is based on a few basic principles:

1. Data from a source must flow without interference from other sources over a reserved slot. Because of possible hidden terminals, the receiver(s) of a flow must be the one(s) telling the potential sources that the slot is reserved while the sender of a flow must be responsible for telling the potential destination(s) that there exists interference in the slot.
2. The sender of a broadcast or multicast flow should not have to receive explicit feedback on the reservation from each neighbor. In CATA, this is accomplished with what amounts to negative acknowledgments to reservation requests, and by each node sending a control packet at the start of a slot in which it is busy receiving data.

To accomplish slot reservations according to the above principles, CATA divides a slot into five mini-slots. The first four mini-slots are intended for control packets and are called control mini-slots (CMS1 to CMS4). The last mini-slot is meant for data and is called data mini-slot (DMS). In practice, the DMS should be much longer than any CMS to reduce the protocol overhead.

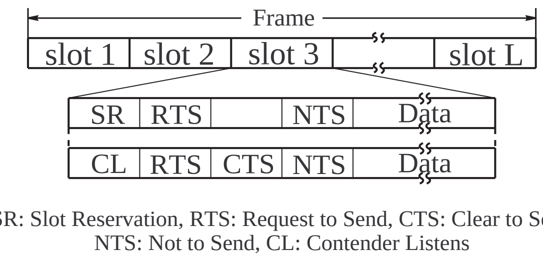

Fig. 1. Slot and frame structure of CATA

Fig. 1 illustrates how slots are identified as reserved and collision-free data are sent over reserved slots. CMS1 is used to provide a "busy tone" to senders attempting to establish transmissions. Every node that receives data during the DMS of the current slot sends a slot reservation packet (SR) in CMS1; this control packet causes noise or is received by its neighbor nodes, which prevents them from attempting to reserve the current slot for data transmission. In addition, every node that sends data during the DMS of the current slot sends a request-to-send packet (RTS) during CMS2 to jam any possible RTSs addressed to its neighbors, who may not notice that the sender has reserved the current slot, which can in turn cause interference to the neighbors. Both the sender and receiver(s) of a flow keep quiet during CMS3 and the sender sends a not-to-send packet (NTS) during CMS4. Data can flow from the sender to receiver(s) of a flow during the DMS.

Fig. 1 also shows how slots are reserved for broadcast, multicast and unicast. The sender of an intended reservation sends request only if it is not engaged in data exchange during the DMS of the current slot. The source listens over the channel to ensure that there is no busy tone; it sends an RTS during CMS2 if the channel is clear during CMS1.

If an RTS for unicast is received correctly at the intended receiver, the receiver sends a clear-to-send packet (CTS) during CMS4; otherwise, no CTS is sent in CMS4. The sender of a unicast RTS detects a successful unicast reservation with the reception of the CTS. Data can flow during the DMS of the current slot, and the same slot in subsequent frames, until the unicast flow is terminated. If a node receives a correct RTS for broadcast or multicast during CMS2 or detects the channel clear during CMS2, then it remains quiet during CMS3 and CMS4; otherwise, it sends an NTS during CMS4 as a negative acknowledgment to any potential broadcast or multicast reservation being made. The sender of a broadcast or multicast RTS detects the failure of its broadcast or multicast reservation request when it either receives an NTS or detects noise during CMS4. If the sender of a broadcast or multicast RTS detects the channel clear during CMS4, it concludes that the reservation is successful and can start transmitting during the DMS.

We note that the algorithms and radio equipment needed for CATA are much the same as those needed for collision-avoidance MAC protocols. In an ad-hoc network of up to a

few hundred nodes, a control packet needs to be only a few bytes to specify sender and receiver(s); on the other hand, time slots should be capable of supporting average-size IP packets and multiple acknowledgments to such packets. Therefore, the overhead of control mini-slots is small compared to the needed length of the data mini-slot.

B. Frame Length

Frame length is an important performance parameter for any MAC protocol based on time scheduling, because it directly affects delay and channel reuse. The frame length for the fixed TDMA protocol in a network with N nodes is N slots.

For a node A to broadcast successfully using single-channel half-duplex radios, no node B within two hops from A can broadcast at the same time slot as A does; otherwise, A and B cannot receive the broadcast data packet sent by each other if they are one-hop neighbors, or their common neighbors can experience a collision if A and B are two-hop neighbors. Therefore, for every node to broadcast successfully in one slot every frame, the frame length L required in CATA must be larger than the number of nodes in a two-hop neighborhood, which in the worst case equals $Min\{d^2+1, N\}$ slots, where d is the maximum node degree (number of neighbors a node has) of the network and N is the number of nodes in the network. This result is the same obtained for the TDMA/FDMA scheme in [12].

Theorem 1: The worst-case minimum frame length needed for each node to unicast successfully in one slot every frame in CATA is $Min\{d^2+1, N\}$ slots.

Proof: Let us consider an arbitrary transmission from an arbitrary node A to any of its neighbors B. To schedule this transmission, both A and B must be idle in the intended slot. It is obvious that both A and B can each have at most $d-1$ busy-receiving slots in a frame not including the transmission from B. Furthermore, the transmission to be scheduled is not allowed to interfere with any reception at A's neighbors. In the worst case, there can be $(d-1)^2$ such slots. Note we already exclude the cases in which the intended transmission can be interfered. Therefore, in the worst case, with frame length of $Min\{d^2+1, N\}$ slots, CATA can always find a collision-free slot for the intended transmission. □

Theorem 2: The worst-case minimum frame length for each node to unicast successfully to each of its neighbors once every frame in CATA is $Min\{2d^2, N\}$ slots.

Proof: Similarly, let us consider an arbitrary transmission from node A to its neighbor B. It is obvious that both A and B can each have at most $2(d-1)$ busy (i.e., transmitting or receiving) slots in a frame not including the transmission from B to A. In addition, neither can the transmission to be scheduled interfere with any reception at A's neighbors nor any transmissions from B's neighbors can interfere with the transmission to be scheduled. In the worst case, there can be $2(d-1)^2$ such slots. Therefore, in the worst case, with frame length of $Min\{2d^2, N\}$ slots, CATA can always find a collision-free slot for the intended transmission. □

The upper bound of the frame length for unicast in CATA is similar to that of [13], which is $Min\{Nd/2, 2d^2-2d+1\}$.

III. CORRECTNESS OF CATA

The following theorem demonstrates that CATA can make correct reservations and eliminate hidden-terminal interference problems. We assume that there is no capture effect, which implies that overlapping transmissions at a receiver causes the receiver to hear only noise.[1] It is also assumed that RTS from a source can be successfully received by its addressed neighbor(s) within finite time. All the neighbors of node A are denoted by the set $N(A)$. We consider a static network. We assume that every pair of nodes have a common idle neighbor and will relax this restriction later.

Theorem 3: CATA guarantees that every addressed neighbor of a source can receive data with no collisions.

Proof: Because every data receiver in a slot sends an SR during CMS1 and a node wishing to reserve the slot is allowed to send RTS only if the channel is clear in CMS1, a new reservation attempt from a sender cannot collide with any existing data transmissions at their destinations.

Every data sender i in a slot sends an RTS during CMS2, which can cause RTS collision at any neighbor j of i if any other neighbor k of node j sends an RTS in the slot. Thus, it follows that j cannot become a destination of k's data transmission in the slot. Therefore, any existing data transmissions cannot collide with any newly established data transmission at its destination.

For a broadcast or multicast reservation, if a neighbor of a contender for a slot is a data sender in the intended slot, then the data sender sends an NTS during CMS4, which stops the contender from reserving the intended slot for data transmission. Therefore, broadcast or multicast data can be sent only if all neighbors of the contender are ready to receive data.

Let us consider all neighbors of any broadcast or multicast contender are ready to receive data in the intended slot. If two nodes x and y within two hops of each other contend for the same slot, then their common neighbor z, who is listening during CMS2, hears a collision and sends an NTS in CMS4, which forces both contenders to abort their intended reservations. On the other hand, if x is the only node that contends for the slot within its two-hop neighborhood, then all its neighbors receive the RTS correctly and no neighbors send NTS, which leads to a successful broadcast or multicast slot reservation for x and guarantees that all x's addressed neighbors can receive the data collision-free.

For a unicast reservation, if a contender r's destination neighbor d receives r's RTS correctly, then it must be true that no node other than d in $N(r)$ can receive a correct RTS in the same slot, for otherwise the RTS from r would interfere with it. Therefore, d is the only node in $N(r)$ who sends CTS in CMS3 and the CTS is collision-free at r. It must also be true that no node other than r in $N(d)$ is sending an RTS in the same slot, for otherwise there will be a collision of RTS at d. Thus the unicast transmission data from r can be received collision-free by its destination.

In summary, newly established data transmissions cannot collide with one another at any of their destinations. □

[1] This assumption is reasonable for the type of commercial narrow-band radios in which we are interested.

A. Discussion

It is possible (though not often) that the nodes contending for a broadcast or multicast slot do not have any common neighbor, or their common neighbors are also sending request in the same slot. If this is the case, a contending node who sends an RTS is not able to know whether any of its one-hop or two-hop neighbors is sending an RTS simultaneously. This will cause an undesired saturation in which some neighbor(s) of the broadcasting node or some addressed neighbor(s) of the multicasting node cannot receive the broadcast or multicast data because they are broadcasting or multicasting at the same time. This very problem was pointed out by Zhu and Corson [14] and solved in the protocol they proposed.

Rather than resolving this unusual situation as part of the handshake rules as it is done in [14], CATA resolves these rare conflicts by asking the nodes to send beacons listing all the broadcast and multicast slots they have reserved and destinations periodically within the DMS. Furthermore, after a successful reservation of a broadcast or multicast slot, the source sends such a beacon during the DMS, picking randomly when in the DMS to send the beacon. Once a node i finds in a beacon received that any neighbor j transmits data in the same slot as i does and at least one of them is the destination of the simultaneous data transmissions, i may reschedule its conflicting transmission accordingly. A simple rule, such as "smallest node ID keeps the right for a slot" can be used to resolve conflicts. Accordingly, conflicting broadcast or multicast reservations can be reduced and finally eliminated.

IV. Approximate Throughput Analysis

A. System Model and Assumptions

We assume that new or retransmitted requests to establish reservations arrive at each node according to Poison process with average arrival rate g requests per slot. Each node has exactly one buffer which can store only one message. For simplicity, we assume that each node can reserve at most one slot for data transmission in each frame. We call a node that has no reserved transmission slot in a frame an idle node in the frame. An idle node will try to make reservation for a request arrival in the next slot.

We consider variable-length flow and assume that, on the average, it takes δ slots to send all the data packets in a flow, i.e., the average flow length (AFL) is δ slots. We also assume that the flow length is geometrically distributed, which implies that the probability that a flow ends at the end of a transmission slot is $q = 1/\delta$.

To simplify our analysis, we consider a fully-connected network topology with N nodes. Given that CATA guarantees collision-free data transmission after reservation in the presence of hidden terminals, a fully-connected network is the worst case scenario in terms of interference, contention or spatial reuse. Therefore, the throughput of CATA for a fully-connected network with N nodes is a lower bound of the throughput of CATA for a general topology where the number of nodes in a two-hop neighborhood is N. We will use a frame length, L, equal to N slots. To focus on the MAC protocol, channel errors are ignored and we assume there is no capture effect, so that collision of packets is the only source of errors.

Throughput is defined as the probability that any given node has a reserved slot for transmitting data in any given frame.

B. Analysis

Since there is no spatial reuse in a fully-connected network, broadcast, multicast and unicast have the same behavior. The system can be fully described by one state variable k ($0 \leq k \leq L$), the number of reserved slots, i.e., the number of nodes who have a reserved transmission slot, in a frame. We model the evolvement of the system as a discrete-time Markov chain, where each state of the Markov chain can transit to any state. A transition may occur when any data sender ends its flow or any idle node successfully reserves a transmission slot. Let π_k denote the probability that the system is in state k.

Given a non-persistent policy for nodes to make reservations, an idle node contends for a slot with probability $p_a = 1 - e^{-g}$. Let $G = Ng$. The probability that with i idle nodes there is a successful reservation in an unreserved slot is given by

$$\theta(i) = \binom{i}{1} p_a (1 - p_a)^{i-1} \quad (1)$$

The probability that among i idle nodes there are s successful reservations in t unreserved slots can be expressed recursively as

$$\Theta(i,t,s) = [1 - \theta(i)]\, \Theta(i, t-1, s) + \theta(i)\Theta(i-1, t-1, s-1) \quad (2)$$

with the ending condition

$$\Theta(i,t,s) = \begin{cases} [1-\theta(i)]^t, & s = 0 \\ 0, & t < s \end{cases}$$

If the system is in state k, the probability that n data senders end their flows during a frame, denoted by $D_k^{(n)}$, is

$$D_k^{(n)} = \binom{k}{n} q^n (1-q)^{k-n} \quad 0 \leq n \leq k \quad (3)$$

When calculating the transition probabilities, we will condition on the number of data senders ending their flows in a frame, n. For the transition from state k in frame f to state l in frame $f+1$, at least $\hat{n} = max(0, k-l)$ nodes must end their flows in frame f; therefore, $\hat{n} \leq n \leq k$, and $s = l-(k-n)$ nodes should each successfully reserve a slot in frame $f+1$. The transition probability from state k to state l is thus given by

$$P_{lk} = \sum_{n=\hat{n}}^{k} D_k^{(n)} \Theta(N-k+n, L-k+n, l-k+n) \quad (4)$$

We can solve the global balance equations $\pi_l = \sum_{k=0}^{L} \pi_k P_{lk}$ with the condition $\sum_{l=0}^{L} \pi_l = 1$, which yields the throughput of the system $S = \frac{1}{L}\sum_{k=1}^{L} \pi_k k$.

C. Numerical Results

Fig. 2 shows the throughput of CATA in a fully-connected network with 16 nodes. The throughput versus normalized offered load curves are plotted for various values of average flow

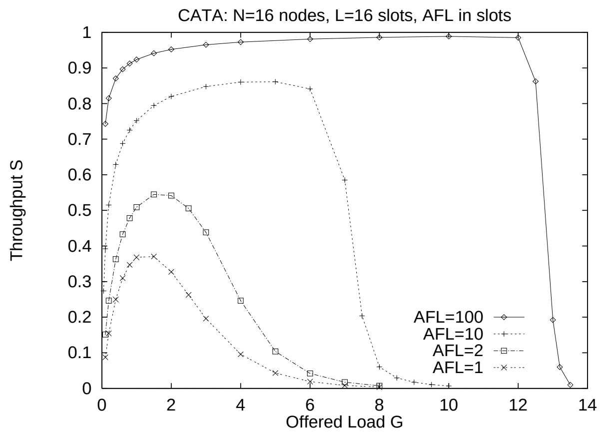

Fig. 2. Throughput performance of CATA with various AFLs

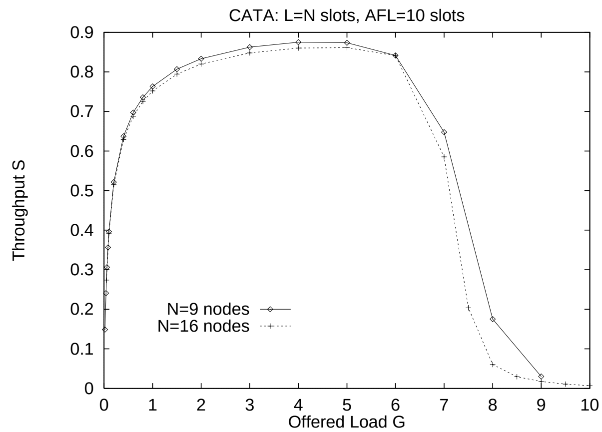

Fig. 3. Throughput performance of CATA with various node densities

length (AFL). As it should be expected, throughput grows significantly when AFL increases. For large AFLs, the throughput is close to that of fixed TDMA, whose throughput is close to one under very heavy load. However, keep in mind that CATA needs a much shorter frame length for practical ad-hoc networks (where $N >> d^2$) and thus has much higher channel reuse ratio.

Fig. 3 exhibits the throughput of CATA in fully-connected networks with 9 and 16 nodes. The AFL is fixed at 10 slots. The curves indicate that with the same total traffic load, the throughput is almost the same for the different network densities (node degree for a ad-hoc network or population for a fully-connected network). This is because each system has enough slots per frame. The figure shows that the node density has little effect on the throughput performance of CATA as long as the minimum frame length required is used. However, a network with higher node density need larger frame length.

The results show that CATA achieves very high throughput for the range of traffic load within which the network is stable. Our analysis is based on the assumption that nodes contend for slots using a non-persistent policy, which implies that a node can attempt to make reservation in every slot and makes our results the worst case results. The throughput and stability of CATA can be improved further with more sophisticated backoff strategies or collision resolution schemes [18]. Reservations in ad-hoc networks tend to be long term since a node is both a host and a router, especially for broadcasting because they are needed for network control packets, for example, which leads to high throughput.

V. Conclusions

We have described a new distributed MAC protocol for ad-hoc networks called collision-avoidance time allocation (CATA). CATA dynamically allocates time slots for unicast, multicast or broadcast traffic through a reservation and handshake mechanism that eliminates hidden-terminal interference and achieves spatial reuse of the available network bandwidth.

We have verified the correctness of CATA's reservation mechanisms and shown analytically that CATA achieves very high throughput, especially with long-lasting flows, and that it requires smaller frame sizes than prior MAC protocols based on topology-independent transmission scheduling.

CATA is designed to operate well with simple single-channel half-duplex radios. CATA's simplicity and ability to provide channel-access delay guarantees and support for collision-free broadcast and multicast traffic makes it much more attractive than such collision-avoidance MAC protocols as IEEE802.11, MACA, MACAW, and FAMA.

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